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Extended Atmospheres of Outer Planet Satellites and Comets

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16. Abstract

Significant accomplishments in the first year of a three-year project in the area of model analysis of the extended atmospheres of outer planet satellites and comets are discussed herein. Work on understanding the neutral hydrogen distribution in the Saturn system concentrated on assessing the spatial dependence of the lifetime of hydrogen atoms and on obtaining appropriately sorted Lyman-α data from the Voyager 1 UVS instrument. Progress in the area of the extended cometary atmospheres included analysis of Pioneer Venus Lyman-α observations of Comet P/Encke with the fully refined hydrogen cloud model, development of the basic carbon and oxygen models, and planning for the Pioneer Venus UVS observations of Comets P/Giacobini-Zinner and P/Halley during the second project year.

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I. Introduction

The research goals of this project are to provide physical insight into the nature of the extended gaseous atmospheres of both outer planet satellites and comets. For the outer planets, research efforts are focused upon understanding the large circumplanetary atomic hydrogen distribution in the Saturn system, both in terms of its neutral sources (which include the satellite Titan) and its role as a plasma source for the planetary magnetosphere. For comets, the emphasis is to understand the basic chemical composition of the nucleus and its interaction with the sun and solar wind through study of the composition and spatial structure of its extended cometary hydrogen, oxygen and carbon atmospheres.

To understand the circumplanetary atomic hydrogen in the Saturn system, the strategy adopted has been to model carefully the spatial structure of the hydrogen torus of Titan (the expected dominant source of H atoms) and compare it with the Voyager UVS data for the hydrogen Lyman-α emissions. This comparison will not only determine the Titan source but will also provide a means of identifying and assessing the relative importance of other possible non-Titan hydrogen sources (i.e., the icy satellites, the planetary rings, and the planetary atmosphere). To achieve this objective, the Titan hydrogen torus model at AER has been improved to include the spatial lifetime of H atoms in the planetary magnetosphere by utilizing the Voyager PLS electron and ion data explicitly determined by E.C. Sittler in a collaborative effort established for this purpose. In addition, a collaborative effort has also been established with D.E. Shemansky to provide optimally-prepared Voyager UVS Lyman-α data for this comparison.

The basic chemical composition of the comet nucleus, which is too small to be seen and is furthermore obscured from view by the gas and dust coma, will be investigated by studying the observed nature of the very-extended atmospheres of the comet. For this strategy (which is widely adopted) to be successful, however, it is vital to have a model for the cometary atmosphere that accurately contains all the relevant physical interactions that occur in the sun/solar wind environment for the so-called parent molecules that are ejected from the nucleus. Recognizing this requirement, a very general particle trajectory model (PTM) has been developed at AER. In this project, this model is being utilized to analyze the density and UV emissions of

extended cometary hydrogen, oxygen, and carbon atmospheres. To test and further refine these models, a collaborative effort with A.I.F. Stewart has been established to analyze cometary H, C, and O emissions obtained by Pioneer Venus OUVS measurements for Comets P/Encke, P/Giacobini-Zinner, and P/Halley.

The discussion of first year progress and achievements is divided into two parts: the hydrogen distribution in the Saturn system and cometary atmosphere. An exhibit presenting information about the first subject was displayed at the AAS/DPS meeting last year (Shemansky, Smith, Smyth and Combi, 1984). A paper discussing our successful modeling of the Comet P/Encke Lyman-α data obtained with the UV instrument of the Pioneer Venus Spacecraft by A.I.F. Stewart was also presented at the AAS/DPS meeting (Combi, Stewart and Smyth, 1984) and an expanded version of this paper (submitted for publication) is included in the Appendix.

II. Hydrogen Distribution in the Saturn System

1. Overview

The three-year plan for our research in the Saturn system is summarized in Table 1. As can be seen, the first year objectives are primarily limited to improving the Titan hydrogen torus model and optimally preparing the Voyager 1 Lyman-α data so that model-data comparisons may be performed in the second year. All of the first year objectives were successfully completed with the exception that some of the preliminary model calculations scheduled for the end of the first year were rescheduled for early in the second year when complete cross-sectional information for a newly identified hydrogen lifetime process is to be available. Progress in these two primary areas undertaken during the first year is summarized separately below.

2. Hydrogen Torus Model for Titan

A circumplanetary cloud of hydrogen is produced by escape of H atoms from Titan's upper atmosphere. The density and the spatial extent of the cloud about Saturn are determined by the flux and initial velocity distribution of H atoms escaping Titan and by loss processes for H atoms in the planetary environment. Escape of hydrogen from Titan's exobase is expected to occur both thermally, where the mean thermal speed of the 186°K exospheric H atoms (Smith et al., 1982) is equal to the gravitational escape speed, and non-thermally, by H atoms produced by exothermic ion-neutral reactions in the upper atmosphere (Strobel and Shemansky, 1982). Four loss processes for atomic hydrogen in the Saturnian system are summarized in Table 2. The first is ionization with magnetospheric electrons, the second is charge exchange with either magnetospheric ions (H^+, O^+, N^+) or solar wind ions (H^+), and the third is ionization by solar photons. The fourth is removal of torus H atoms from the cloud by elastic collisions with fast H atoms in the interstellar medium, which upon impact can transfer sufficient energy to cloud atoms that they escape the gravitational field of the planet. This last process was just identified in the third quarter of this project and was an outgrowth of our collaborative effort with D.E. Shemansky.

The pre-Voyager Titan hydrogen torus model (Smyth, 1981) was improved in an earlier NASA project to include the spatial lifetime of H atoms in the Saturn magnetosphere. In the past year, the remaining lifetime processes of

TABLE 1

SATURN SYSTEM: THREE-YEAR PLAN FOR MODELING ANALYSIS

Subject	First Year	Second Year	Third Year
(1) Titan Torus	Continue to refine plasma information in the lifetime description. Obtain properly sorted Voyager 1 Lyman α data. Perform preliminary model calculations.	Perform exploratory model calculations with various exospheric escape parameters. Analyze the Lyman α data and determine the source rate and spatial distribution of hydrogen from Titan.	Perform a complete analysis of the Lyman α data and extract relevant information to describe the escape and magnetospheric interaction of H atoms from Titan and other important neutral sources.
(2) Non-Titan Satellite and Ring Sources	--	Identify possible non-Titan sources of H atoms from the above analysis. Develop suitable models to investigate the properties of these sources.	Determine for these neutral sources the spatial character and magnitude of their plasma input rates.
(3) Planetary Source	--	Use the collaborative effort with Shemansky and the above analysis to assess the importance of a planetary source	

Table 2

LOSS PROCESSES FOR ATOMIC HYDROGEN IN THE SATURNIAN SYSTEM

1. $H + \left\{ \begin{array}{l} e \text{ (cold)} \\ e \text{ (hot)} \end{array} \right\} \longrightarrow H^+ + 2e$

2. $H + \left\{ \begin{array}{l} H^+ \\ O^+ \\ N^+ \end{array} \right\} \longrightarrow H^+ + \left\{ \begin{array}{l} H \\ O \\ N \end{array} \right\}$

3. $H + h\nu \longrightarrow H^+ + e$

4. $H + H \longrightarrow H + H$

	ISM ($\sim$20 km sec^{-1})	TORUS (slow)	ISM (fast)	TORUS (fast)

Table 2 have been incorporated in the model, although the complete computation of the cross-section for reaction four is not expected until early in the second project year (Shemansky 1985). The lifetime of hydrogen in Saturn's equatorial plane, based upon the plasma loss processes of Table 2 and plasma data for the Saturn magnetosphere determined from Voyager encounter data by Sittler (1984) as part of a supporting collaborative effort, is given in Figure 1. For radial distances from Saturn larger than about 15 R_S, the lifetime produced by the planetary magnetosphere is about 1×10^8 sec and is comparable to the lifetime of hydrogen in the solar wind produced by charge exchange with protons. Inside of 15 R_S, the lifetime drops to values as low as $4\text{-}5 \times 10^6$ sec near 7 R_S. The photoionization lifetime of hydrogen at Saturn's distance from the Sun is near 1×10^9 sec and is also indicated in Figure 1. The lifetime of hydrogen produced by the magnetospheric plasma becomes larger as one departs from the equatorial plane as illustrated in Figure 2, with values eventually becoming comparable to the photoionization lifetime.

The newly identified lifetime for hydrogen atoms in the torus involving the interstellar medium can compete favorably with the plasma loss processes summarized in Figures 1 and 2. The interstellar medium (mostly H atoms with a density of 0.1 cm^{-3} and a temperature of ~10,000°K) move through the solar system with a velocity of about 20 km sec^{-1} and past Saturn during the Voyager encounters at about 29 km sec^{-1} (i.e., a relative energy of about 4 ev). Most torus H atoms involved in these collisions can gain sufficient additional energy (~0.3 - 0.03 ev) so that they are gravitationally lost from the Saturn system. Assuming a preliminary estimate for the elastic H-H elastic cross-section at these low energies of $(5\text{-}10) \times 10^{-15} cm^{-2}$, the estimated lifetime of torus atoms is bracketed between 3.6×10^8 sec and 7.1×10^8 sec. Together with the solar wind and photoionization processes, a uniform background lifetime of $\lesssim 1 \times 10^8$ sec exists outside of the magnetosphere. Inside of the magnetosphere, the composite lifetime is spatially variable and is less than 3×10^8 sec everywhere within the outer contour shown in Figure 2. The composite lifetime near the equatorial plane of Saturn is then $\lesssim 1 \times 10^7$ sec between 4 R_S and 10 R_S and $\lesssim 1 \times 10^8$ sec between 10 R_S and Titan's orbit at ~20 R_S.

The lifetime of hydrogen atoms in the Saturn system therefore ranges from values as short as 1.5 months inside of Titan's orbit to values of order 3 to

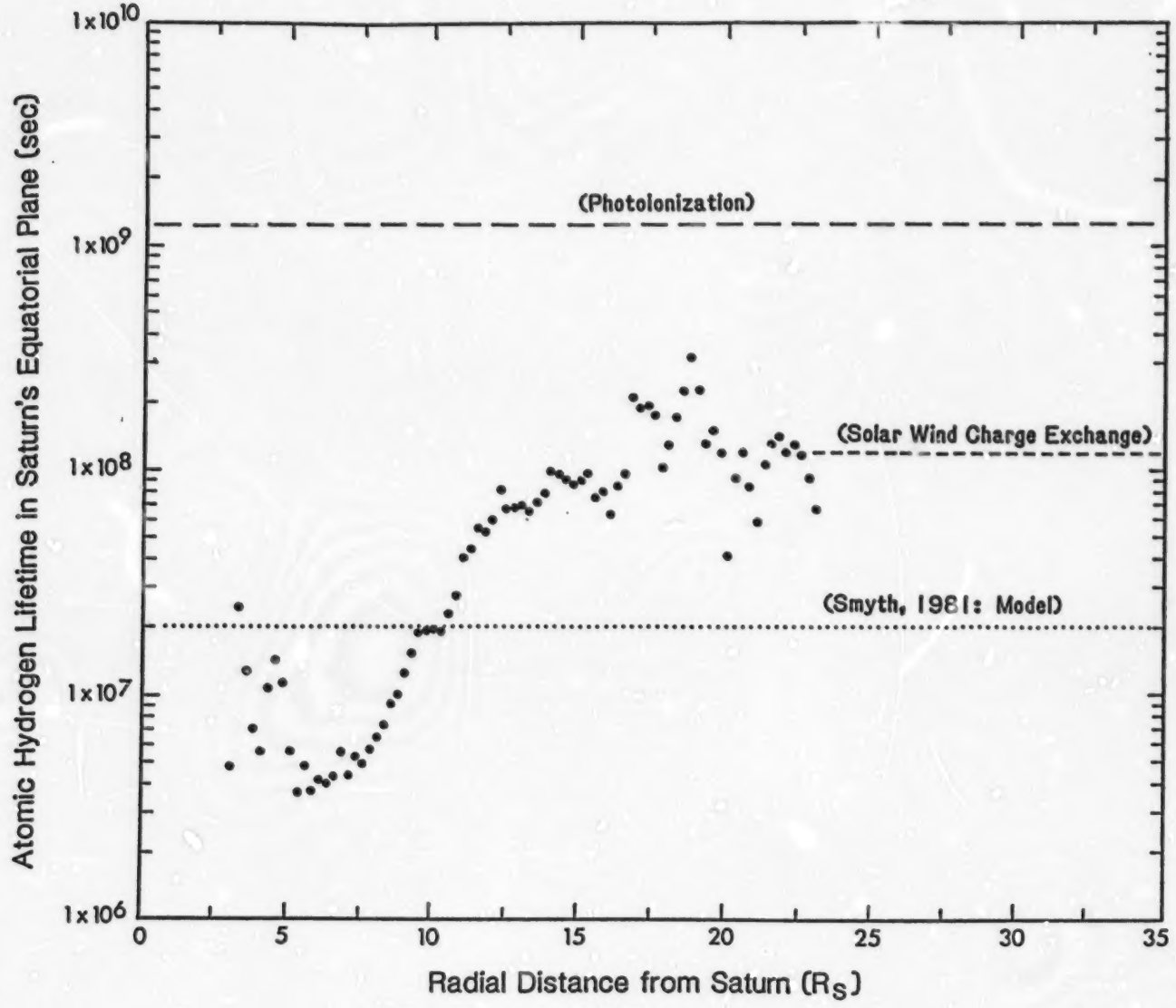

Figure 1. Lifetime of Atomic Hydrogen in Saturn's Magnetosphere.

The lifetime is appropriate for the plasma reactions of Table 1 and the plasma information based upon an analysis of the Voyager PLS data by Sittler (1984).

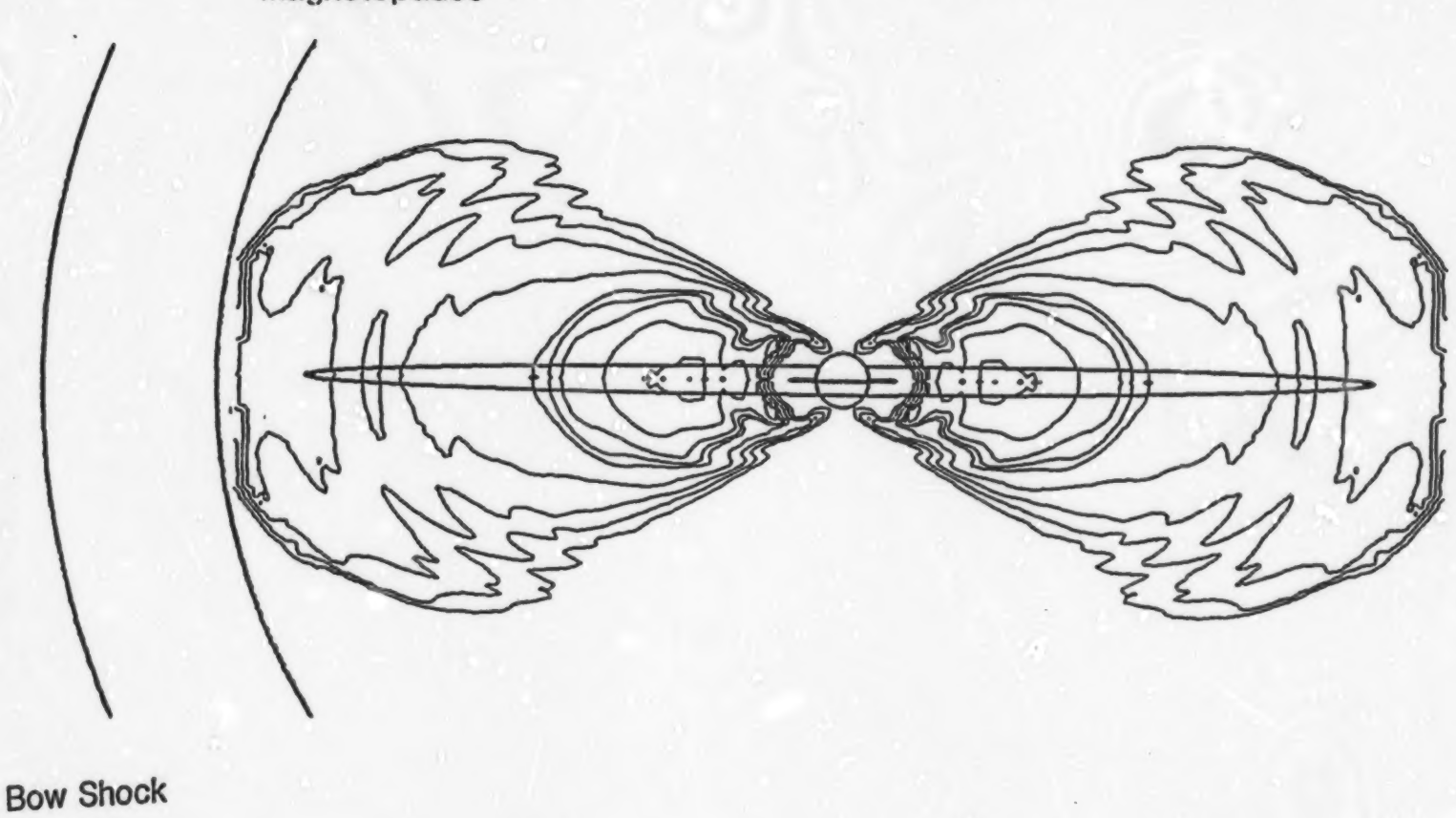

Figure 2

Lifetime of Atomic Hydrogen in Saturn's Magnetosphere

The lifetime is calculated for the plasma loss processes described in Table 1. The electron and ion (H^+, O^+, N^+) densities and temperatures were obtained privately from a new analysis of Voyager plasma data performed by Sittler (1984). Contour values are, from outside to inside, 1×10^9, 7.5×10^8, 5×10^8, 2.5×10^8, 1×10^8, 7.5×10^7, 5×10^7, 2.5×10^7 and 1×10^7 sec.

10 years throughout regions of the magnetosphere. The potential impact of the new lifetime process are threefold: (1) to reduce somewhat the long integration times for H-atom trajectory orbits that would otherwise be required to model the torus properly, (2) to play a significant role in regulating the number of H-atoms in the torus, and (3) to provide a 30 year modulation of the number of H-atoms in the torus because of orbital motion (~9.6 km sec^{-1}) of Saturn about the Sun. During the first year, some testing of the Titan hydrogen torus model has been performed to determine the best procedure for including these long lifetime hydrogen atoms accurately but at the same time economically. Additional effort has been expended in evaluating the recapture of hydrogen atoms by Titan. These efforts will be continued in the second year in preparation for full model calculations to be used in analyzing the Lyman-α data from hydrogen obtained by the Voyager UVS instrument.

3. Lyman-α Data for Hydrogen

The best data for the circumplanetary hydrogen distributed in the Saturn system has been acquired by the UVS instrument aboard the Voyager 1 and 2 spacecrafts during their encounters with the planet. The Voyager 1 data provided east-west scans (i.e., radial brightness profiles) while the Voyager 2 data provided north-south scans (i.e., a vertical thickness profile). Most of the Voyager 1 and 2 data for the circumplanetary hydrogen require significant processing to make them available for a model-data comparison. For example, only about 25 percent of the Lyman-α radial brightness profile obtained by Voyager 1 were processed and reported earlier by Broadfoot et al. (1981).

To properly process and prepare these data, a collaborative effort with D.E. Shemansky has been established. During the first year, all of the useful Voyager 1 and 2 Lyman-α data for the circumplanetary hydrogen was optimally sorted and processed. At the end of this first project year, only removal of the background level and planetary disk signature in the east-west scans remained. This will be completed early in the second year. A preliminary look at the data indicates that the east-west scan data are of excellent quality and should be well suited for our analysis purposes. The north-south scan data were obtained with greater spatial resolution, but with less integration time. These data will be averaged in various ways to increase their signal-to-noise content and should provide valuable information about the vertical as well as the radial structure of the hydrogen distribution.

III. Cometary Atmospheres

1. Overview

The three-year plan for our research in cometary atmospheres is summarized in Table 3. Significant accomplishments have been made during the first year in all three subjects. All refinements in the cometary hydrogen model, based upon H_2O as the parent molecule, were completed in the first two quarters, and the model was used to successfully analyze new Comet P/Encke Lyman-α observations obtained on April 15, 1984 by A.I.F. Stewart from Pioneer Venus OUVS measurements (see the Appendix). By the end of the third quarter, a cometary oxygen model, based upon the parent molecule H_2O, had been developed and a preliminary model calculation for the 1304 A emission brightness of Comet P/Encke was performed. The development of the cometary oxygen and carbon models, based upon the parent molecules CO_2 and CO, was initiated in the second quarter and successfully completed in the fourth quarter. The objective of the last remaining subject in Table 3 is to identify and acquire new observational H, C and O data for the self-consistent studies to be undertaken in the third year. During the first year, a tremendous opportunity to acquire these data for Comet P/Halley from Pioneer Venus OUVS measurements was identified and a collaborative program with A.I.F. Stewart for this purpose was established. A more detailed account of progress in these three subjects is summarized separately below.

2. Hydrogen Atmospheres

The hydrogen model was developed under previous NASA projects (NASW-3174 and NASW-3387) to calculate hydrogen atom trajectories in three dimensions including the effects of solar gravity and solar radiation pressure (see Figure 3). That original model included the correct extended source distributions for H produced by photodissociation of H_2O and OH but assumed only the simplest speed distributions of 20 and 8 km s^{-1}, respectively, from the two sources. This year the model has been expanded to include the full branching ratios and speed distribution for photodissociation as shown in Table 4. Also incorporated this year is the heliocentric velocity dependent lifetime for OH, as shown in Figure 4.

The newest version of the model was used during this first year to analyze the H Lyman-α observations of Comet P/Encke made by Dr. A.I. Stewart

TABLE 3

COMETARY ATMOSPHERES: THREE-YEAR PLAN FOR MODELING ANALYSIS

Subject	First Year	Second Year	Third Year
Hydrogen	Perform detailed model calculations for currently available data to test the model assumptions and numerical input parameters (branching ratios, velocity dispersion, etc.) Perform exploratory model calculations to investigate the effects of the variable solar UV flux on photochemical reaction rates, radiation pressure acceleration, and fluorescence excitation		Apply the models developed and refined in the first two years to new data for a self-consistent study of the relative roles of H, C, and O as observed in the extended atmosphere, and their ultimate sources in the cometary nucleus.
Carbon and Oxygen	Develop basic models	Perform initial model calculations for currently available data. Investigate the roles of likely molecular sources for cometary C and O.	
General	Identify and acquire new observational data.		

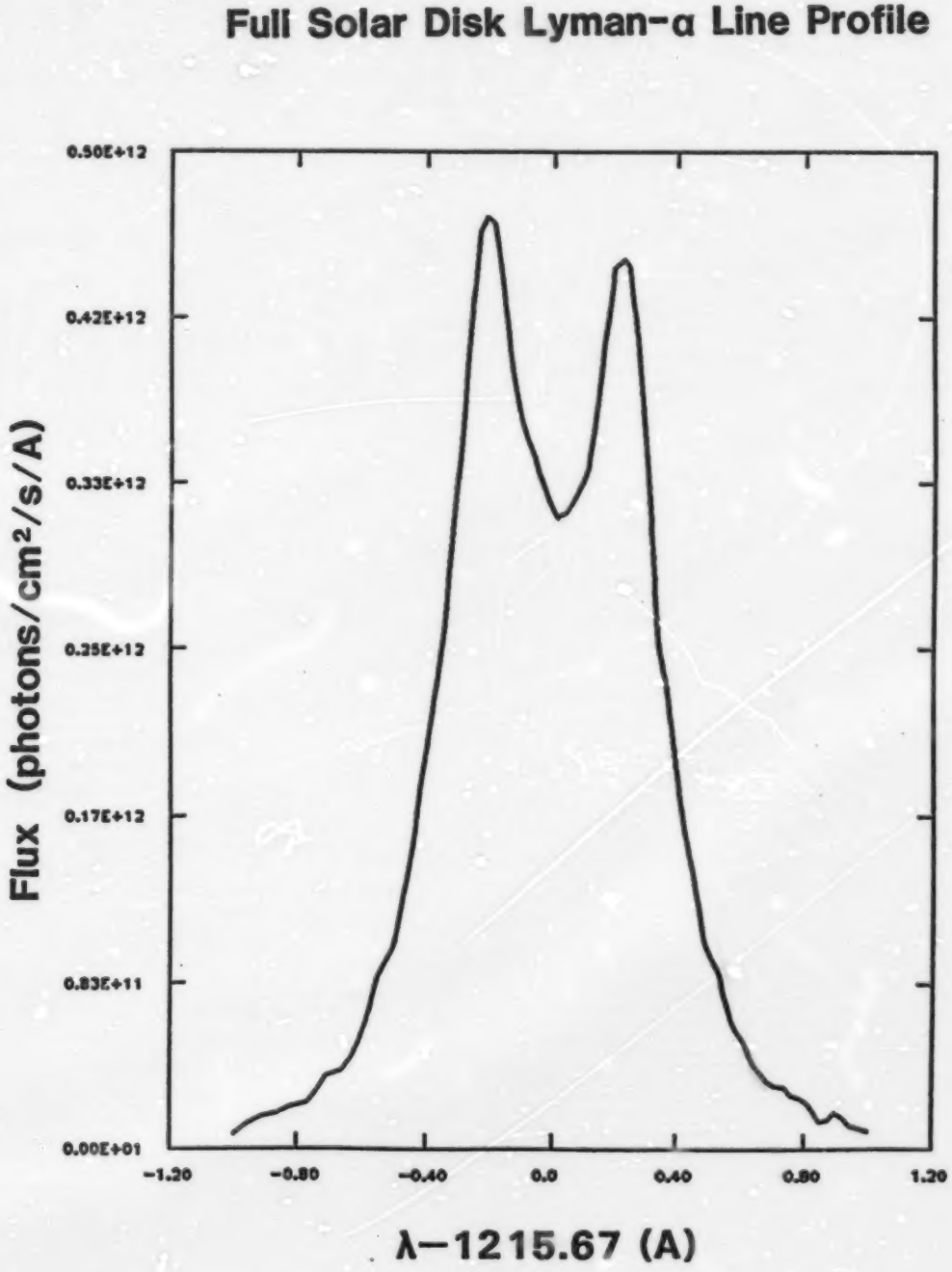

Figure 3. Full Solar Disk Lyman-α Line Profile. The profile was determined by Lemaire et al. (1978).

Table 4

Photoabsorption of Solar UV Radiation by H_2O Vapor

	Wavelength Range	Reaction	Product Velocities (km sec^{-1})		Fraction of Total H_2O Photoabsorbed	
			H Atom	OH Molecule	Quiet Sun	Active Sun
1.	1357Å < λ < 1860Å	$H_2O + h\nu \longrightarrow H + OH(X^2\pi)$	20	1.2	.670	.534
		$\longrightarrow H_2 + O(^1D)$	—	—	.007	.005
2.	λ = 1216Å	$H_2O + h\nu \longrightarrow H + OH(X^2\pi)$	30	1.8	.167	.269
		$\longrightarrow H_2 + O(^1D)$	—	—	.023	.036
		$\longrightarrow H + OH^*(A^2\Sigma^+) \longrightarrow H + O + H$	≤ 5.0	—	.027	.044
		$\longrightarrow H + OH(A^2\Sigma^+)$	5.0	0.3	.009	.015
3.	984Å < λ < 1357Å, λ ≠ 1216Å	$H_2O + h\nu \longrightarrow H + OH(X^2\pi)$	25-35	1.2-2.0	.028	.021
		$\longrightarrow H_2 + O(^1D)$	—	—	.004	.003
		$\longrightarrow H + OH^*(A^2\Sigma^+) \longrightarrow H + O + H$	4.0-6.0	—	.004	.003
		$\longrightarrow H + OH(A^2\Sigma^+)$	0-17.0	0-1.0	.002	.001
4.	λ < 984Å	$H_2O + h\nu \longrightarrow$ ionization products [H_2O^+, etc.]	—	—	.059	.069

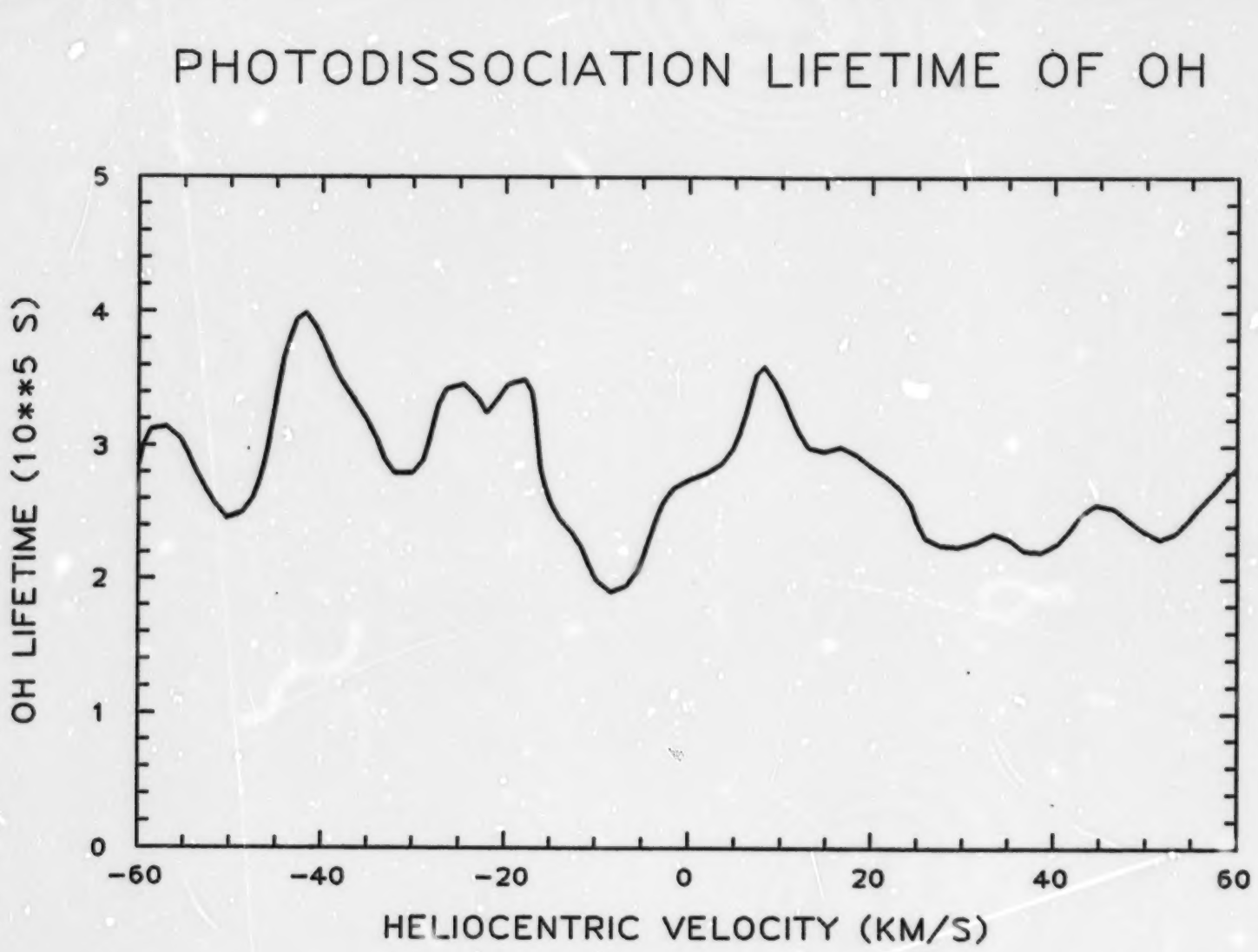

Figure 4. The Heliocentric Distance Dependence of the OH Lifetime. These calculated values are by Schleicher and A'Hearn (1983).

with the UV Spectromenter on the Pioneer Veuns orbiter. A preprint of a forthcoming paper is included in the Appendix of this report. The Pioneer Venus hydrogen observation represented the first reliable measurement of an H or OH production rate during the post-perihelion phase of the comet. Our analysis implied the self-consistent production of H by H_2O photodissociation. The resulting H production rate indicated that the water production rate did not seem to exhibit the same pre- to post-perihelion asymmetry as had been seen in both the visual light curve and in the production of the minor carbon bearing radicals (A'Hearn et al. 1983). We also re-evaluated the expected ionization lifetime for hydrogen atoms due to photoionization, charge exchange with solar wind protons and electron impact with solar wind electrons and found that a value which is a factor of two smaller than the generally accepted value is both predicted and fits the spatial distribution seen by Pioneer Venus.

3. Carbon and Oxygen Atmospheres

Basic models for the extended atomic carbon and oxygen clouds in comets were begun this year. The spatial distributions of cometary C and O have been observed in the emissions at 1657 Å and 1304 Å, respectively, in Comet Kohoutek 1973XII (Opal and Carruthers 1977). Smith et al. (1980) have measured the distribution of carbon in Comet West 1976VI at 1657 Å and also C('D) at 1931 Å. Weaver et al. (1981) have reported IUE observations of C and O in a few faint comets, but these were only single nucleus-centered brightness values.

As for most cometary observations, all of these data have been analyzed in terms of Haser's model, which cannot be used to provide reliable physical information regarding lifetimes, outflow velocities, or exothermic ejection velocities. Using the particle-trajectory method, we can provide a physically realistic framework in which true source and sink characteristics and their spatial and temporal dependencies can be understood.

To the best of our knowledge, the sources of the bulk of the observed carbon and oxygen lie in the photolysis of cometary H_2O, OH, CO and CO_2 (Delsemme 1982). Carbon production from the visibly prominent carbon radicals, CN, C_2, and C_3, only accounts for a minor fraction of total carbon in comets (Feldman 1978, A'Hearn and Feldman 1980). Although the existence of CO_2 ice in comets is strongly suggested by the presence of CO_2^+ in ion tails,

Feldman (1978) has put forth some convincing arguments in favor of CO as the ultimate parent of much of the cometary carbon. With this in mind, we have constructed photochemical scenarios for the production of carbon and oxygen with H_2O, CO and CO_2 as primary parent molecules and will constrain our conclusions by the appropriate observations.

Table 5 shows a list of the branching ratios and exothermic velocities for the production of C and O from H_2O, CO_2 and CO. The total photolysis rates for these three parents are 1.2×10^{-5} s^{-1}, 2.0×10^{-6} s^{-1} and $6.5 \times 10^{-7} s^{-1}$, respectively. The data for CO and CO_2 are from Huebner and Carpenter (1979); those for H_2O are from Festou (1981) to which the O('D) branching ratio has been updated (Slanger 1982).

Cometary emission at 1657 A by CI is through resonance fluorescence with the same carbon emission triplet present in the solar UV flux. For OI at 1304 A a combination of resonance fluorescence with the solar OI line and fluorescence by solar Lyman-β are responsible for the cometary emission. A heliocentric velocity dependent emission rate or g-factor results for both emissions, plots of which are shown in Figures 5 and 6 for O and C, respectively.

The first model run for oxygen produced by the photodissociation of water was performed for the geometry of the Pioneer Venus observations of Comet P/Encke. A two hour integration at 1304 A produced no detectable signal at the location of the nucleus. The modeled 2-D sky plane view of the oxygen emission, shown in Figure 7, was normalized to the water production rate of 3.0×10^{28} s^{-1} inferred by the H Lyman-α observation. An expected slit-averaged intensity of 1.6 Rayleighs for the Pioneer Venus OUVS instrument should have been recorded; however, this is fully one order of magnitude below the background noise limit for the observation. Fortunately, Comet P/Halley is expected to be 50 to 100 times more productive than P/Encke, and observations of both C and O should be easily made.

In addition to developing these models for analysis of the Pioneer Venus observations of P/Halley, we will also be applying them to a simultaneous set of H, O, and C observations of Comet Kohoutek made during a rocket flight on January 8, 1974 (Meier et al. 1976, Opal and Carruthers 1977). The models used by Meier et al. (Keller and Meier 1976) for the H distribution assume somewhat reasonable speed distributions and lifetimes for H atoms, and their implied production rates are probably correct. However, the analysis of the O

Table 5

Production of Cometary Carbon and Oxygen

REACTION	f_o[a]	v_o[b]	f_c[a]	v_c[b]
$H_2O + h\nu \rightarrow H_2 + O(^1D)$	.034	1.6	–	–
$\rightarrow H + OH$; v_{OH} = 1.2–1.8 km s^{-1}				
$OH + h\nu \rightarrow O + H$				
$CO + h\nu \rightarrow C + O$	.907	.5	–	–
$\rightarrow C(^1D) + O(^1D)$	.434	3.66	.434	4.88
	.064	5.52	.064	7.36
$CO_2 + h\nu \rightarrow O + CO$; v_{CO} = 3.71 km s^{-1}	.465	6.50	–	–
$CO + h\nu \rightarrow C + O$	.202	3.66	.202	4.88
$\rightarrow C(^1D) + O(^1D)$	.030	5.52	.030	7.36
$\rightarrow O + CO(a^3\pi)$; v_{CO} = 2.18 km s^{-1}	.138	3.82	–	–
$CO + h\nu \rightarrow C + O$	.060	3.66	.060	4.88
$\rightarrow C(^1D) + O(^1D)$	.009	5.52	.009	7.36

a. Fractional yield of atoms per primary parent molecule

b. Velocity of atom produced in km s^{-1}

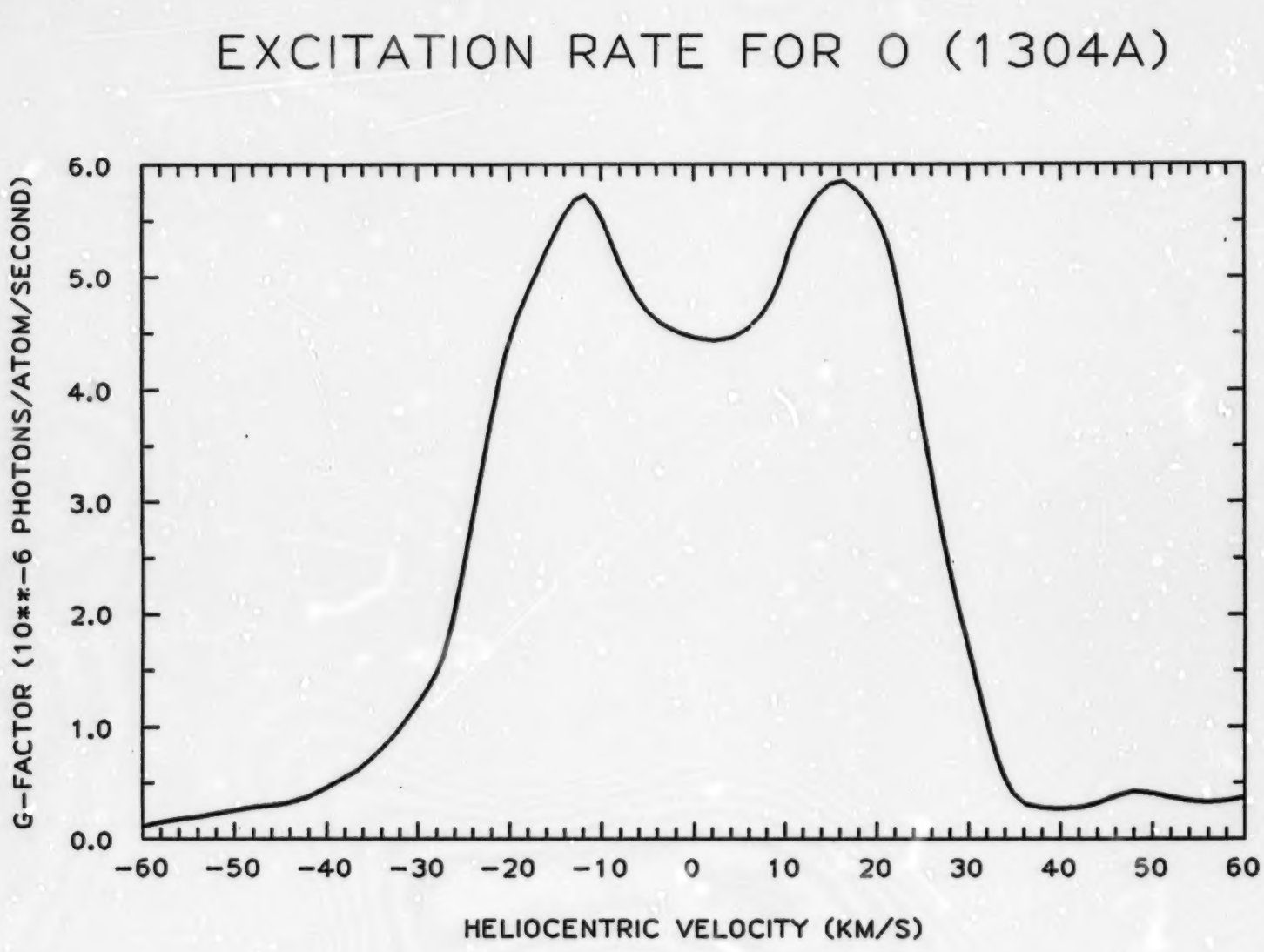

Figure 5. The Heliocentric Velocity Dependent g-factor for the OI 1304 Å Triplet. These results by Feldman (1982) show the contributions from solar resonance scattering as well as fluorescence by solar HI Lyman-β.

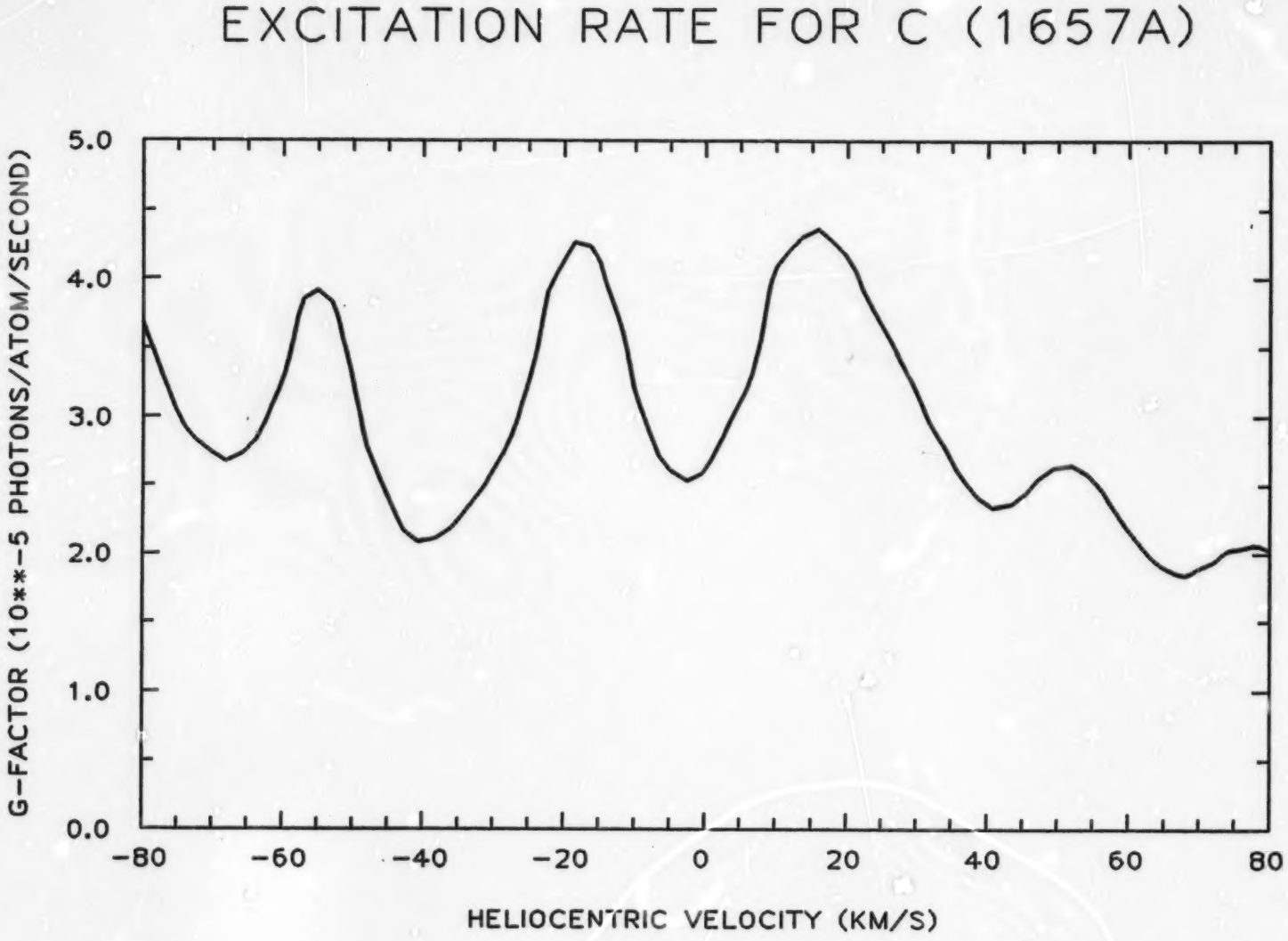

Figure 6. The Heliocentric Velocity Dependent g-factor for the CI 1657 Å Triplet. These results by Feldman (1978) show the effect of cometary CI resonance scattering by the solar CI lines.

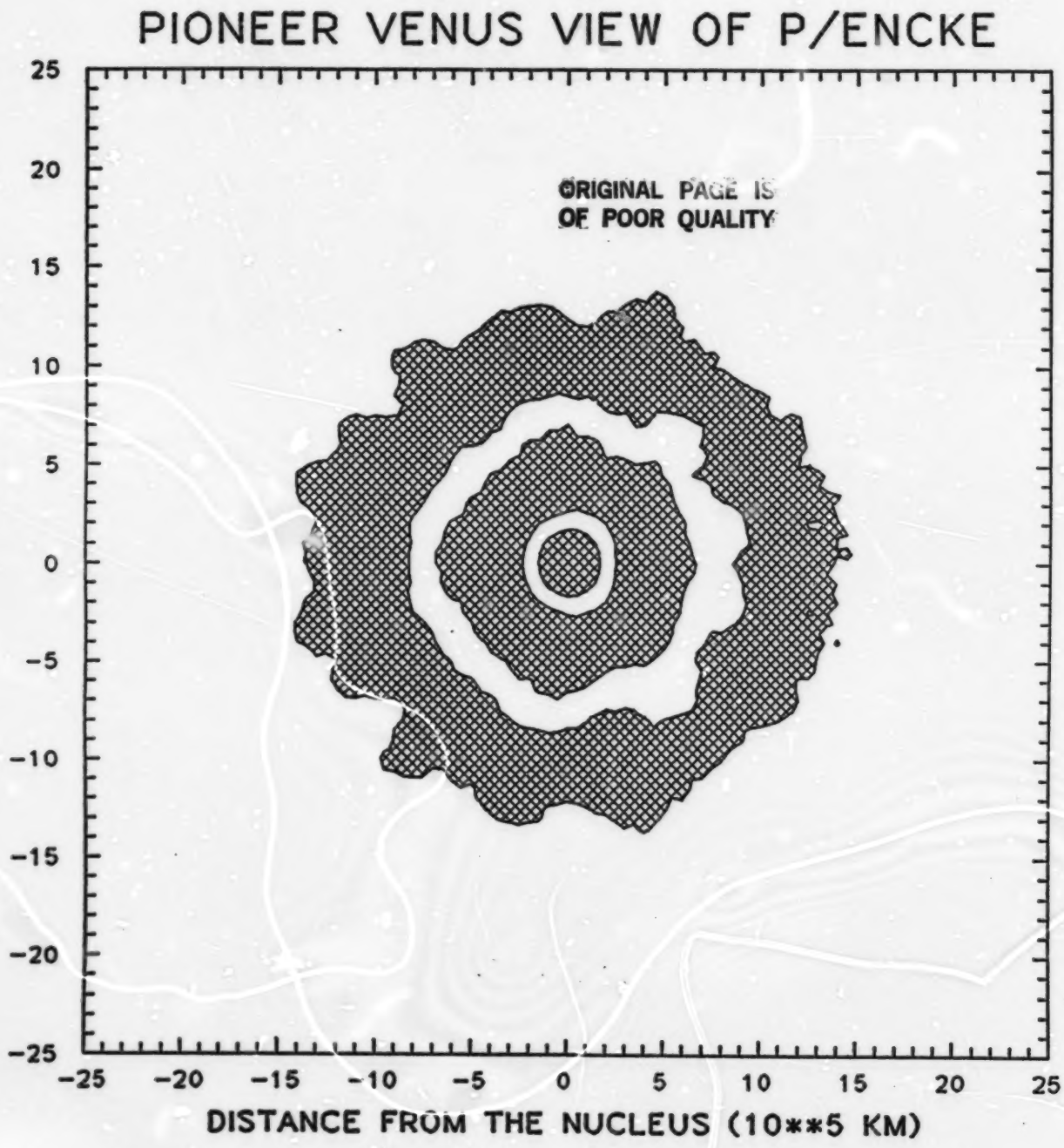

Figure 7
The Modeled OI 1304 Å Emission from Comet P/Encke.

The H_2O source of cometary oxygen corresponding to the Pioneer Venus Orbiter UVS observation (r_H = .58 AU, Q_{H_2O} = 3 x 10^{28} s^{-1}) has been calculated with the particle-trajectory model. The shaded areas correspond to intensities of 0.1-0.5, 1.0-5.0 and >10.0 Rayleighs from the outside to the inside.

and C data by Opal and Carruthers was done with the oversimplified Haser model assuming 1 km s^{-1} outflow velocities; therefore, relative production rates between the different species are highly suspect, as they stated in their paper. The mean outflow speeds expected for C and O atoms produced by photodissociation, as shown in Table 5, are likely to be from 2 to 7 km s^{-1}. Therefore, in addition to the relative production rates, the lifetimes for C and O which are routinely adopted from this analysis of Opal and Carruthers (Feldman 1982) are also likely to be model dependent. It is the self-consistent analysis of this type of data to which we address our modeling program.

Model runs for C and O distributions as produced by photodissociation of H_2O, CO and CO_2 have been performed for the geometry of the Comet Kohoutek observations of January 8, 1974. Preliminary analyses of these results have yielded some interesting conclusions.

(1) The bulk of the observed carbon likely results from the photodissociation of CO but not CO_2. The time to dissociate both CO_2 and CO in succession is too long to account for the observed distribution. The average radial profile for the modeled CI 1657 Å emission is shown in Figure 8 for equal production rates of CO_2 and CO. The CI distribution for a CO_2 parent shows a large "hole" for a nuclear distance out to nearly 3×10^5 km, whereas the distribution for a CO parent more reasonably resembles the observation.

(2) Because of the shorter lifetimes of H_2O relative to either CO or CO_2 and because of the smaller ejection speed for O atoms from H_2O and OH (see Table 5), the bulk of the observed cometary oxygen will likely come only from water photodissociation. Even for <u>equal</u> production rates of H_2O and CO (or CO_2), the observed column densities (and 1304 Å fluorescent emission rate) for O atoms is an order of magnitude larger for the H_2O source at a nuclear distance of 10^5 km (see Figure 9).

4. Comet P/Halley Program

The research plan in Appendix A was developed to integrate optimally the modeling support program at AER together with the comet UV observations to be obtained from the Pioneer Venus Orbiter between the spring of 1984 and 1986. In brief, these observations include

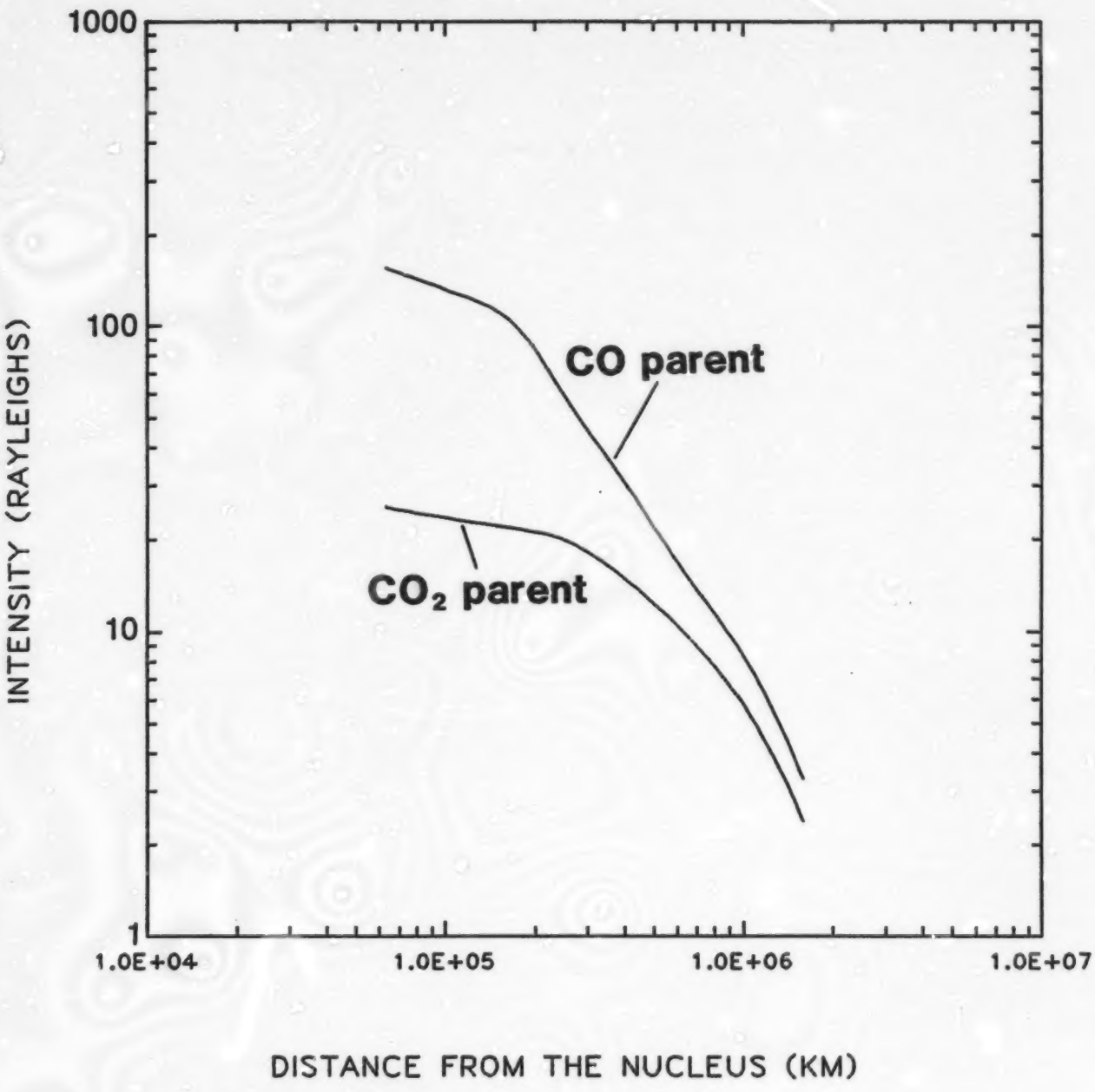

Figure 8. Modeled Carbon 1657 Å Emission

The average radial emission profile for the 1657 Å triplet is shown for two models of carbon production. The upper curve is for CO as the primary parent; the lower curve is for CO_2 as the primary parent. The models are normalized to equal production rates for the parent molecules and correspond to the Comet Kohoutek observations of Opal and Carruthers (1977).

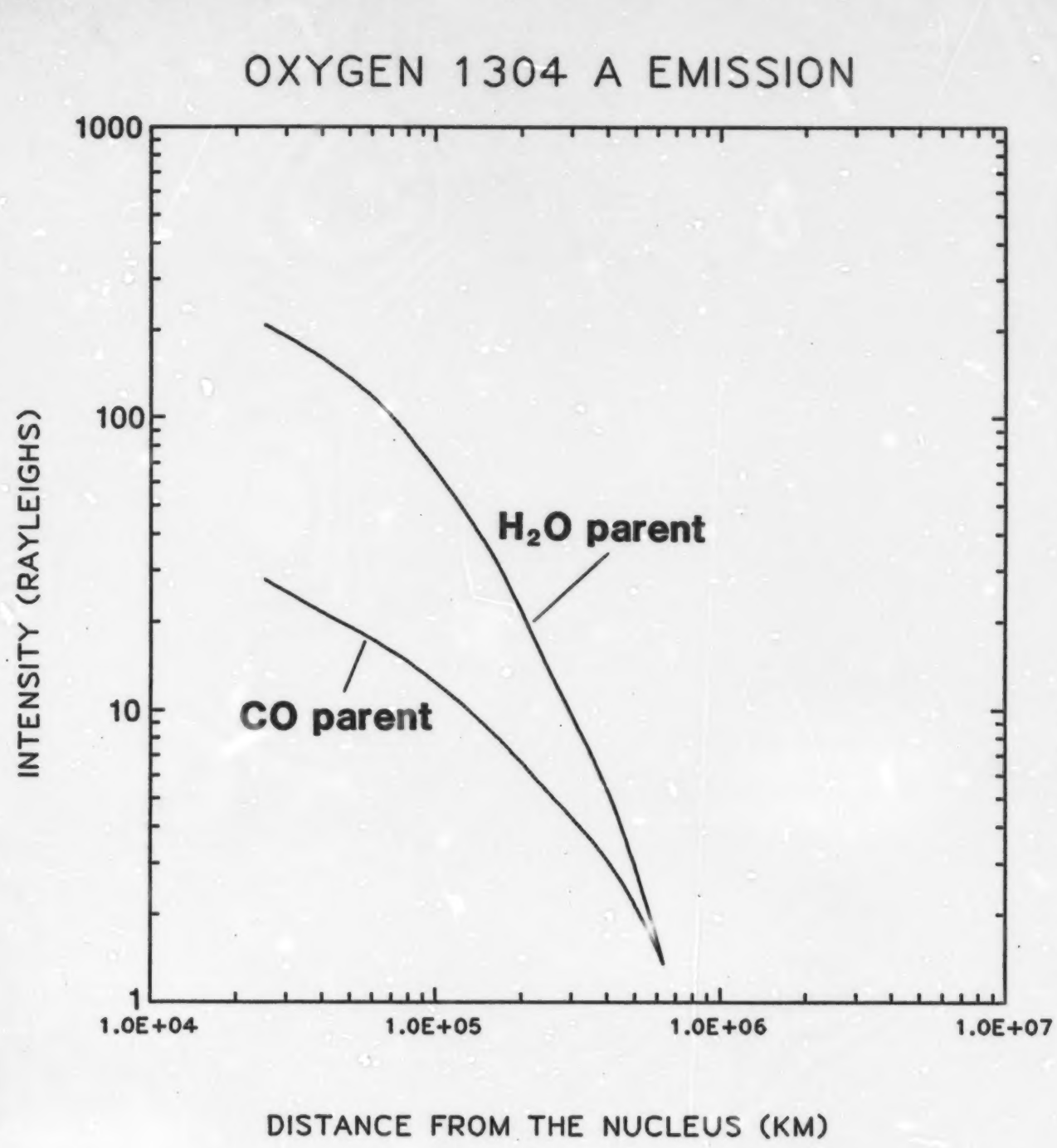

Figure 9. Modeled Oxygen 1657 A Emission.

The average radial emission profile for the 1304 A triplet is shown for two models of oxygen production. The upper curve is for H_2O as the primary parent; the lower curve is for CO as the primary parent. The models are normalized to equal production rates for the parent molecules and correspond to the Comet Kohoutek observations of Opal and Carruthers (1977).

(1) the successful measurement of Comet P/Encke in hydrogen (1216 Å) on 15 April 1984,

(2) the expected measurement of hydrogen (1216 Å) from Comets P/Giacobini-Zinner and P/Halley on 11 September 1985 and Comet P/Halley in late December 1985, and

(3) most importantly, the continuous measurement of Comet P/Halley in 1986 (before, during and after perihelion at 0.59 AU) from early February to the middle of March in hydrogen (1216 Å), oxygen (1304 Å) and carbon (1657 Å).

The September and December observations of Comet P/Halley will be used to determine the H_2O source rate at ~2.5 AU and ~1.0 AU respectively, where the UV emissions are weak and only the brightest H emission (1216 Å) is expected to be detected. The continuous observations of Comet P/Halley in 1986 (in all three atomic emission lines) will provide the rich data set that will be used for a self-consistent study of H, C, and O during the third project year. The observation of Comet P/Giacobini-Zinner on 11 September will be used to estimate the cometary gas production rate. This will be particularly useful in interpreting plasma and magnetic field properties to be measured by the ICE spacecraft, which will fly by the comet on that date.

The above measurements of Comet P/Halley in 1986 are unique and very important. They provide the only continuous coverage of the comet's activity during a period where the comet cannot be easily viewed from the earth because of the position of the Sun in the sky plane. In early February, the Spartan instrument, to be launched by the space shuttle, may, in addition, monitor Comet P/Halley for at most a few days in its UV emissions excluding H Lyman-α. In early March, the ASTRO-1 satellite will be placed in earth orbit with UV instruments, and by the middle of March, both the Giotto and Vega missions will have had their closest approaches to Comet P/Halley. The Pioneer Venus OUVS measurements and their analysis at AER will be utilized by the Giotto mission for their final pre-encounter planning. A continuous set of H, C and O observations for Comet P/Halley at pre-perihelion, perihelion and post-perihelion will, however, only be acquired by the Pioneer Venus OUVS measurements. Analysis of these measurements at AER should be most interesting and very productive.

In addition to the basic data analysis program, we have also initiated a complementary collaborative effort with Drs. A.I. Stewart and R. Gladstone (LASP) which is aimed at modeling the optically thick portion of the C and O comae. We will provide them with appropriate density and speed distributions of atoms in the coma which they will use in their spherical radiative transfer models. Our normal optically thin results then will be compared to their results to evaluate any optical depth effects.

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APPENDIX A

Comet Observation from the Pioneer Venus Spacecraft

Planning Meeting at AER: January 30, 1985

Present: Michael Combi, William Smyth, Ian Stewart

I. Lyman-α Observations

1. P/Encke Data
   (a) Analysis
   (b) Paper to Nature.
2. September 1985 Observations of P/Giacobini-Zinner and P/Halley
   (a) Analysis
   (b) Paper and/or 1985 DPS presentation
3. Preliminary Modeling for P/Halley
   (a) Prepare model results at AER for different dates (Date 1, 2, 3,...) with different Q values and solar-wind-charge-exchange lifetimes for H; model results to be used for initial interpretation of data
   (b) Send results to Ian before December 1985
4. Careful Modeling for P/Halley
   (a) Ian will send initial data to AER in February 1986
   (b) AER will perform modeling with a turnaround time of order 1 to 2 weeks.
   (c) Model results will also serve to provide preliminary information for Giotto measurements to be obtained ~10 March ± 5 days
   (d) Latest solar wind data may be provided by Intrilligator
   (e) Solar UV fluxes from SME.
5. Final Modeling for P/Halley
   (a) Perform comprehensive modeling of H-data; determine time dependence of Q
   (b) Perform initial modeling of O-data to help form more complete picture of comet
   (c) Paper and/or 1986 Heidelberg presentation.

II. Oxygen 1304 Å Observations

1. Perform model calculation of the velocity distribution, $f(\vec{v},r)$ of O escaping Encke; send to Ian/Randy Gladstone to help develop spherically symmetric radiative code
2. Preliminary modeling of Halley Data
   (a) Ian will send initial data to AER in spring 1986
   (b) Perform preliminary modeling at AER; send results to Ian/Randy Gladstone as input for radiative transfer calculations; iterative procedure may be required
3. Perform careful modeling of Halley Data
4. Perform final modeling of Halley Data

III. Carbon and Sulfur Observations

1. Analysis of the C and S data should follow naturally from the procedure set up for O.

APPENDIX B

An Analysis of Pioneer Venus Orbiter Observations of Hydrogen Lyman-α in Comet P/Encke

by

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A.I.F. Stewart[2]

and

W. H. Smyth[1]

August 1985

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ABSTRACT

The Pioneer Venus Orbiter Ultraviolet Spectrometer observed the extended hydrogen coma of Comet P/Encke at Lyman-α (1216 Å) on 14 and 15 April 1984, when the comet was 0.58 AU from the Sun and 1.02 AU from Venus after perihelion. These data have been analyzed with a new fully time-dependent three-dimensional particle-trajectory model based on the production of H atoms by photodissociation of H_2O and OH. The model analysis yields a production rate of water molecules from Comet P/Encke of 3.0×10^{28} per second at the time of the observation. This value is shown to be self-consistent with pre-perihelion OH data where H and OH are produced by H_2O photolysis, and does not seem to exhibit the pre- to post-perihelion asymmetry of the visual light curve.

The observations of comets in the vacuum ultraviolet have helped to provide direct confirmation of the icy conglomerate nature of the cometary nucleus.[1] Only indirect evidence had been available prior to this.[2] UV observations of the extended hydrogen coma are particularly important since hydrogen is thought to be produced by the photodissociation of water, the dominant constituent of the volatile fraction of most cometary nuclei.[3,4,5] Since the possible so-called parent molecules (H_2O, CO, CO_2, CH_4, NH_3, etc.) cannot be easily observed, most of our knowledge about the the physical and chemical nature of the nuclei and the extended atmospheres surrounding them results from the observation of the fragments of these parent molecules: the neutral radicals, atoms, and ions seen distributed throughout the comae of comets. To this end, observations of the major atomic species and the neutral radicals have been, and will continue to be, of the utmost importance.

Comet P/Encke is a short period comet ($t \sim 3.3$ years) with a perihelion distance of 0.34 AU. It has been suggested that the comet may be an evolved object with much of its surface now devoid of the volatile ices whose vaporization drives the cometa activity which produces the familiar coma and tails leaving a largely non-volatile dusty mantle. Comet P/Encke displays a conspicuous sunward fan for a coma which appears about two times brighter before perihelion than after perihelion.[6] Whipple and Sekanina[7] have explained this asymmetry with a model where the rotation axis of the comet lies nearly in its orbital plane and is oriented such that primarily one pole faces the sun before perihelion and the other pole after perihelion. A compositional difference between the two poles could then explain the asymmetry. Observations of water photodissociation products (H and OH) in Comet P/Encke have been obtained,[8] but not enough post-perihelion data to confirm this asymmetry in water vaporization are available. The 1984 apparition has provided the opportunity to make these observations.

We report here an analysis of observations of the Lyman-α emission of hydrogen from Comet P/Encke obtained with the Ultraviolet Spectrometer on board the Pioneer Venus Orbiter on 14 and 15 April 1984. Most ultraviolet observations of comets have been made from near-earth orbiting or rocket-launched instruments.[9,10] One advantage of remote observation of cometary hydrogen is the lack of absorption of Lyman-α by geocoronal hydrogen. Another advantage is the observation of a comet from a different vantage point. This will be particularly important for the near perihelion observations of Comet P/Halley in 1985/1986 when the comet is very close to the sun in the sky as observed from the earth but when Venus (and the Pioneer Venus Orbiter) will be very well placed.

The Pioneer Venus Orbiter is in an eccentric (2000 x 66000 km), 24-hour orbit around Venus. The inclination is 105° and the latitude of periapsis is 8°N.[16] The spacecraft is spin-stabilized with a nominal spin period of 13.2 sec. The spin axis during normal operation is maintained within a few degrees of the south ecliptic pole.

The University of Colorado's Orbiter Ultraviolet Spectrometer (OUVS) [11] is mounted with its line of sight offset 60° from the spin axis. Its field of view is 1.38° x 0.14°, with the long axis of its entrance slit lying in a plane containing the spin axis. During one spin of the spacecraft, the OUVS field of view therefore traces a swath 1.38° wide along a cone of 60° half-angle, and a point source within the swath dwells in the field of view for 6.0 msec. In the observing mode used for Encke, about 100 measurements were obtained during each spin from a 21° arc of sky; the integration time for each measurement was 1/128 sec. The spectrometer has a spectral resolution of 13 Å. Its grating may be scanned, or it may be set to any one of 512 discrete positions. During acquisition of Lyman-α data from Encke, it was set to the

position closest to the wavelength of Lyman-α (121.6 nm). Its sensitivity to Lyman-α is 130 counts/sec/kiloRayleigh.

Comet Encke became available to the Pioneer Venus OUVS in mid-April 1984, about three weeks after Encke's perihelion (Fig. 1). As the comet emerged from behind the sun, it followed a trajectory that carried it eastward a few degrees south of the ecliptic (Fig. 2). On 15 April it was about 5° ESE of the bright UV star Spica. On 14 April, the spin axis was maneuvered to a position whose ecliptic coordinates were latitude 52.7° south, longitude 241.4° east, which allowed the field-of-view to cross both Spica and Encke. Measurements were made at 1216 Å for one hour near 2100 UT. Six hours later, after an adjustment of the spin axis to 53.3° south latitude, 241.2°east longitude, data were collected for another hour. The spin axis adjustment kept the comet within 0.2° of slit center as it moved across the sky at about 2.7° per day.

The measurements in the neighborhood of Encke contain certain emissions from three sources: the comet's coma, the planet's hydrogen corona, and interplanetary hydrogen. The non-cometary signal, amounting to about 500 R, was measured on both sides of the coma and removed by subtraction. In neither case did it vary significantly across the few degrees subtended by the measurable coma. The statistical uncertainty associated with the subtraction is allowed for in the error bars shown in Figure 3. The line of sight to the comet never came within 20,000 km of the planet's center during the cometary measurements. From coronal measurements on other orbits, we estimate the line-center opacity of the coronal hydrogen along this line of sight to be less than .02; its small effect is ignored in the present analysis.

In order to analyze the spatial distribution of hydrogen in Comet P/Encke, we have employed the particle-trajectory model (PTM) developed by Combi and Smyth.[12,13] Two major but somewhat complementary modeling efforts

have been put forth to date for this purpose by Keller and his co-workers[14,15] and Festou et al.[4] Keller and co-workers have developed cometary hydrogen models that employ a point source region and which use the "syndyname" method to approximate the effect of the gradient of the solar gravity field on the relative trajectory of an atom with respect to the nucleus. In addition, such parameters as the hydrogen lifetime, which depends on the heliocentric distance of an atom, and the Lyman-α emission rate, which depends on both heliocentric distance and velocity of an atom, were evaluated either at the position of the nucleus or at the intersection of a line-of-sight column with the sky plane. Festou et al. have used the vectorial model[16] to describe more realistically the source region in their analysis of the inner coma ($\sim 10^4$ km) Lyman-α profiles from Comet Kobayashi-Berger-Milon (1975IX). Their model assumed a steady state production rate and neglected (appropriately for the inner coma) the effects of solar gravity and solar radiation pressure.

The PTM can be used to calculate correctly the atom trajectories in an arbitrarily large spatial domain ($>10^6$ km) and, at the same time, to describe properly the spatially extended source region ($\lesssim 10^5$ km). The model calculates the atom trajectories in three dimensions by integrating Newton's equation with a fourth-order Runge-Kutta routine which includes both the solar gravitational field and the heliocentric velocity dependent solar radiation pressure. Within the new PTM, we have incorporated a generalization of the Monte Carlo model of Combi and Delsemme[17] in order to prescribe correctly the physics of the source region (i.e., the starting locations and velocities of many H atoms corresponding to the isotropic ejection of photodissociated atoms and radicals). This generalization includes the heliocentric distance dependence of the decay lifetimes of the parents (H_2O and OH in the case of hydrogen) and the production rate. It also includes the heliocentric velocity dependence of the OH lifetime.[18,19]

The trajectory calculation explicitly includes the orbital elements of the comet and the absolute time of the observation. The placement of an atom on the sky plane is calculated taking into account the divergent lines of sight appropriate for the relative comet-sun-observer geometry. The variable radiation pressure acceleration on H atoms as well as the instantaneous emission rate for each atom (the Greenstein Effect) are calculated in the model from the solar disc averaged Lyman-α profile,[20] where the overall flux was scaled to Solar Mesospheric Explorer observations[21] of the sun's Lyman-α flux made at the time of observation. The fluorescence rate of cometary hydrogen by solar Lyman-α is a function of an atom's heliocentric velocity (i.e., the position along the profile) as well as the inverse square of the heliocentric distance.

The initial outflow velocity for the H_2O molecules was taken to be $0.58\ r_H^{-1/2}$ km s^{-1},[22,23] and the lifetime for H_2O appropriate to the quiet sun conditions was 8.2×10^4 s.[4] The H_2O production rate was assumed to vary as the inverse square of the heliocentric distance of the comet, as is appropriate for the comet-sun distances of $\lesssim 0.7$ AU.[6,24] The velocity distributions for the H and OH fragments upon photodissociation of H_2O were taken from the results of Festou[16] with a few minor updates to the branching ratios.

The initial model run assumed the nominally accepted value for the lifetime of H atoms due mainly to charge exchange with solar wind protons of 2×10^6 seconds at 1 AU,[9] but the modeled PVOUVS scan through the coma resulted in an overestimate of the amount of hydrogen with increasing distance from the nucleus, as illustrated by the lighter model curve in Figure 3. We have recalculated the charge exchange lifetime for H at 1 AU from a nominal solar wind density of 8 cm^{-3} and a speed of 320 km s^{-1} and measured charge exchange cross section data,[25,26,27] and found a value of 1.3×10^6 s. In addition, we have determined the electron impact ionization lifetime of

hydrogen due to solar wind electrons (T = 10^5 eV) from Shemansky's expression,[28] and found a value of 4.6×10^6 s. Taking these along with the photoionization lifetime of 1.37×10^7 s,[29] we find a new total ionization lifetime of 9.4×10^5 seconds at 1 AU. It should be emphasized that even if we add the contributions of photoionization and electron impact ionization to the usually accepted value of 2×10^6 seconds for charge exchange alone, the total lifetime for hydrogen atoms still must be lowered to 1.3×10^6 seconds.

For the new value for the H lifetime, the model fit is shown as the heavy line in Figure 3 and provides an excellent fit to the entire profile for both scans. This model analysis implies a water production rate of 3.0×10^{28} molecules per second by Comet P/Encke at the time of the observation (r_H = 0.58 AU). We should stress here that the production rate computed using the longer hydrogen lifetime (which can fit only the near-nucleus points well but exceeds nearly all of the points farther away) only differs from that using the new value by 10%. The lifetime, of course, only affects those atoms which have lived long enough to be depleted, i.e., those farthest from the nucleus.

Figure 4 shows a plot of the H_2O production rate in Comet Encke for several past apparitions,[6] nearly all of which are pre-perihelion data along with this new result. Also shown is the expected asymmetric light curve.[7] It is obvious that this new point is more than a factor of three larger than the expected production rate based upon the post-perihelion light curve. Taken at face value, this could either mean that the water (hydrogen) production rate is not asymmetric about perihelion or that the water production rate was anomalously large during the entire 5-10 day period ending with the Pioneer Venus observation, a period required to build up the H coma.

In fact, data for OH taken subsequently by A'Hearn et al.[30] confirm the persistence of this large post-perihelion value first seen by Pioneer Venus and imply a water production rate which is not asymmetric about perihelion.

Exactly how this affects the calculation by Whipple and Sekanina[7] of the precession of the spin axis and the non-gravitational motion of Comet P/Encke remains to be seen. They assumed that the water vaporization, which represents the bulk of the mass loss of the comet as well as the non-gravitational force, exhibited the same asymmetry that the dust and visible radicals have shown.

The analysis of H and OH observations in terms of the implied water production rates depends primarily on the self consistent modeling of their respective spatial distributions. The post-perihelion water production rate implied by the PVOUS Lyman-α observation is actually about 60% higher than that which would be expected based upon the old pre-perihelion OH data (see Figure 4). The determination of absolute H_2O production rates from OH observations using the generally adopted Haser model depends upon the scale lengths and radical outflow velocity assumed. The scale lengths adopted by A'Hearn[31] for OH photometric data are taken from case B by Weaver et al.[5] The case B scale lengths are reasonably consistent with the velocities and lifetimes used in the PTM, which is based on the expected photodissociation parameters for H_2O.[16] However, A'Hearn also routinely assumes an outflow velocity for all radicals of 1 km s^{-1}. Using the Average Random Walk Model,[17] we should expect an average radial velocity for OH radicals to be between 1.5 and 2 km s^{-1} based on ejection velocities of 1.2 and 1.8 km s^{-1} for OH upon photodissociation[16] and the H_2O velocity law mentioned above. This larger velocity would raise all the OH production rates by this same factor of 1.5 to 2, and bring the OH production rates as determined from the scale lengths adopted by A'Hearn in line with the H production rate found here.

In summary, we have demonstrated the use of the Pioneer Venus Orbiter UV Spectrometer for observing comets by presenting hydrogen Lyman-α observations of Comet P/Encke. These results combined with observations of OH present a

consistent picture of the production of H and OH by the photodissociation of water which vaporizes from the nucleus if the two data sets are analyzed consistently. This vaporization does not show the pre- to post-perihelion asymmetry which has been observed in the dust and the visible radicals. We have analyzed these data with a new particle-trajectory model which for the first time treats both the physical description of the source region and the full time dependence and orbital dynamics of the observed extended cloud correctly.

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[32]The observations of Comet P/Encke were made under NASA contract NAS2-9477. We gratefully acknowledge the help of the Pioneer Project Office and the cooperation of the Pioneer Venus Science Steering Group. The modeling analysis at AER was supported under NASA contract NASW-3966. We also thank Dr. M.F. A'Hearn for communicating his results to us prior to publication.

Figure Captions

Figure 1. The relative positions of Comet P/Encke, Venus, the earth and sun at the time of the Pioneer Venus Orbiter observations are shown.

Figure 2. A view of the sky from Pioneer Venus is depicted with the locations of the sun, earth, the reference star Spica and Comet P/Encke. Also shown is the swath of the sky traced by the Orbiter Ultraviolet Spectrometer Slit.

Figure 3. Comparisons of the Pioneer Venus observations (the plotted points) and particle-trajectory models (solid lines) are shown for the two scans taken six hours apart. The lighter line corresponds to the canonical hydrogen atom lifetime value of 2×10^6 s at 1 AU and provides a poor fit to the data. The heavier line corresponds to a hydrogen lifetime of 9.4×10^5 s. at 1 AU. This new lifetime has been recalculated for this paper and also provides the best fit to the observations.

Figure 4. Water Production Rates in Comet P/Encke. The post-perihelion result from the Pioneer Venus Lyman-α observations is compared with the previous data compiled by A'Hearn et al.[6] as well as the asymmetric light curve of Whipple and Sekanina.[7] The pre-perihelion (upper) light curve has been slid vertically to agree with the ground-based and IUE OH production rates for heliocentric distances larger than 0.75 AU. The two low values at ~0.7 AU represent a somewhat well-documented quiescent period generally seen in Comet Encke.[6] The values shown as upper limits at short heliocentric distances are OH radio observations where the production rates are somewhat more uncertain.

PIONEER VENUS ORBITER

OBSERVATIONS OF COMET P/ENCKE ON APRIL 15, 1984

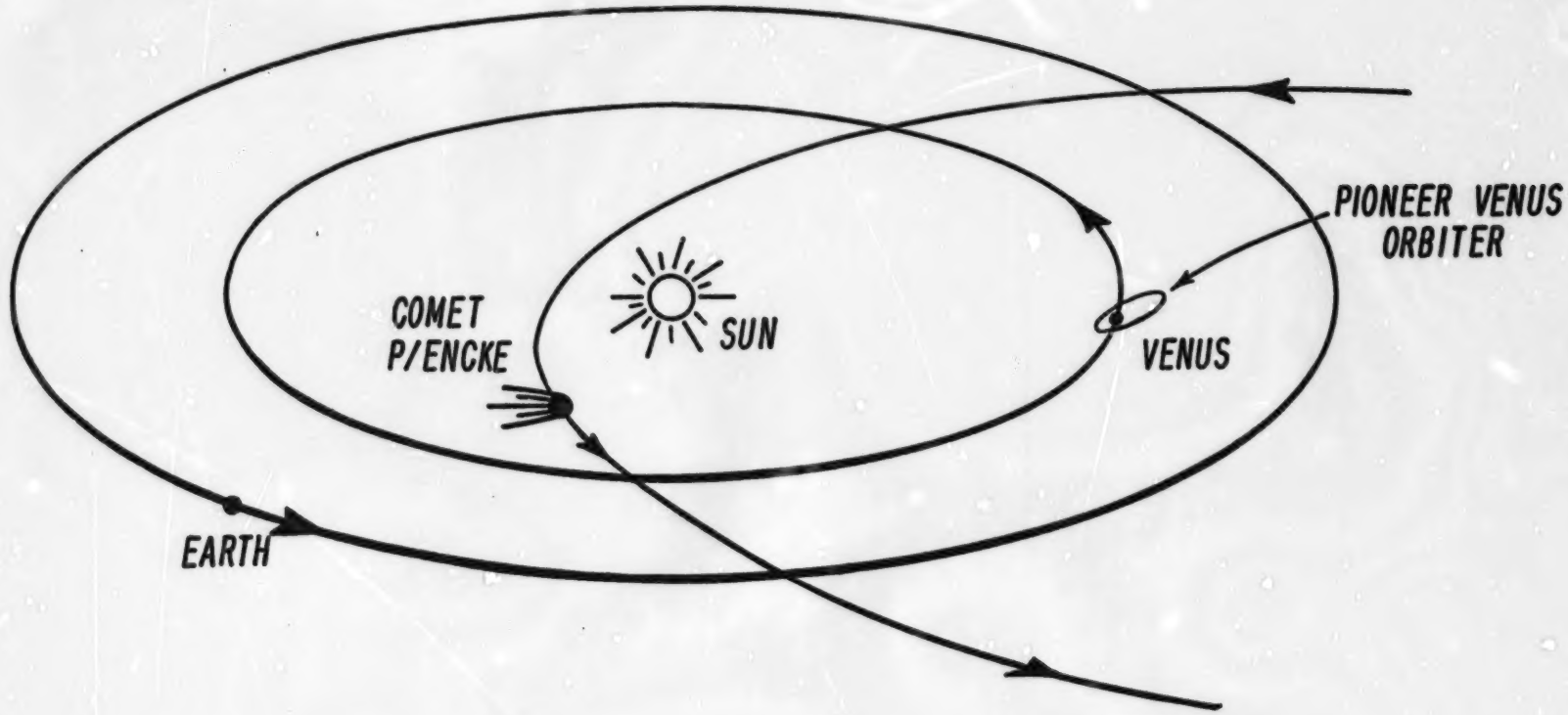

Figure 1

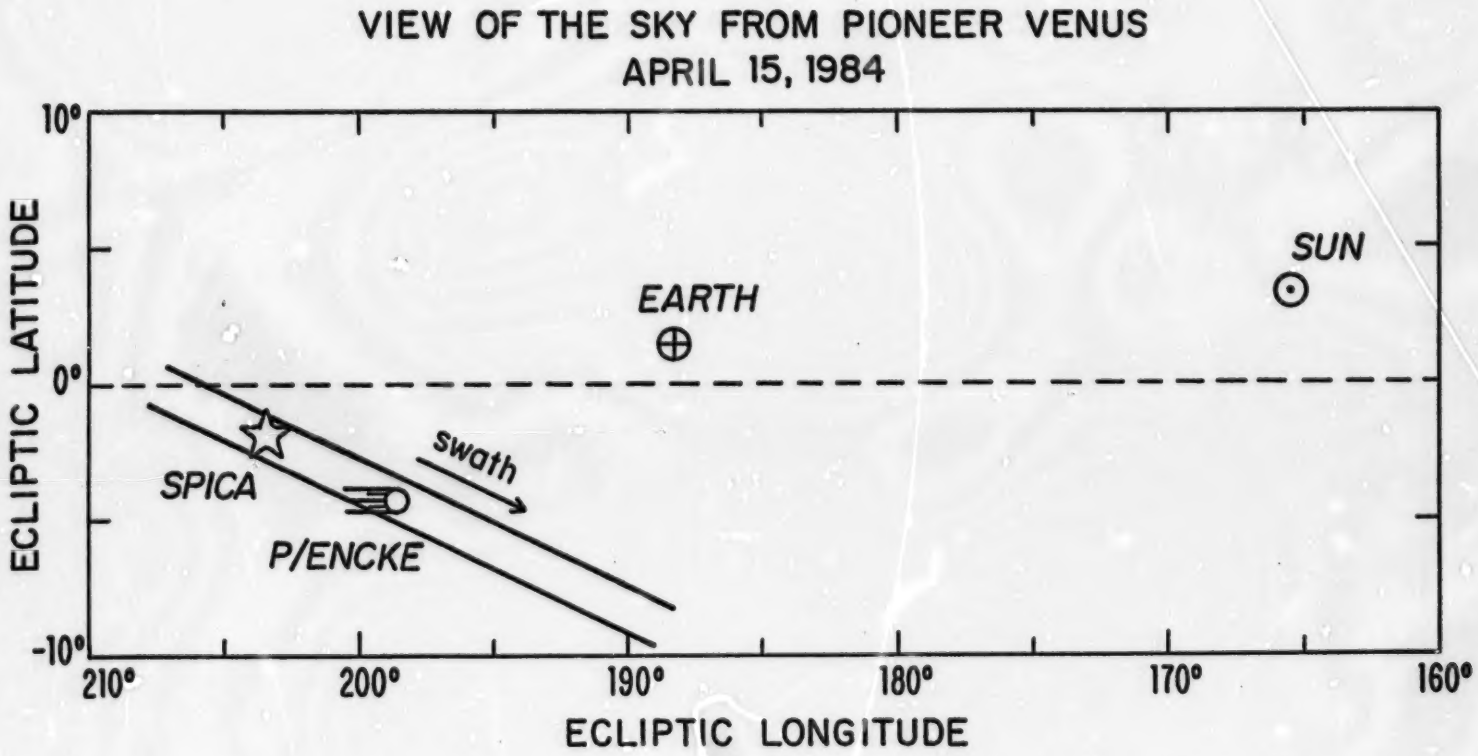
VIEW OF THE SKY FROM PIONEER VENUS
APRIL 15, 1984
10°
0°
-10°
ECLIPTIC LATITUDE
EARTH
SUN
SPICA
swath
P/ENCKE
210°
200°
190°
180°
170°
160°
ECLIPTIC LONGITUDE

Figure 2

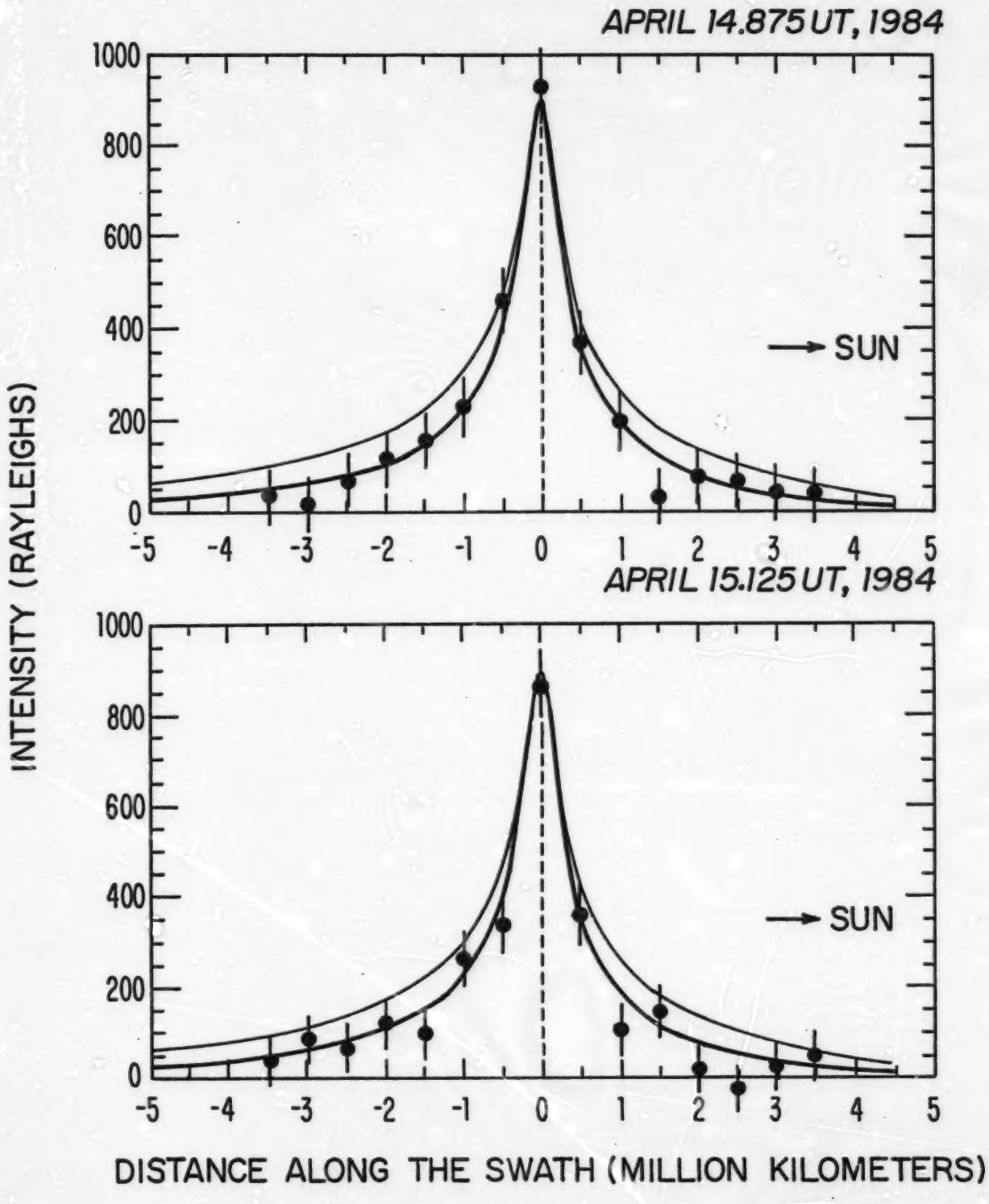
HYDROGEN LYMAN-α BRIGHTNESS OF COMET P/ENCKE
APRIL 14.875 UT, 1984
APRIL 15.125 UT, 1984
SUN
SUN
INTENSITY (RAYLEIGHS)
DISTANCE ALONG THE SWATH (MILLION KILOMETERS)
1000
800
600
400
200
0
-5
-4
-3
-2
-1
0
1
2
3
4
5

Figure 3

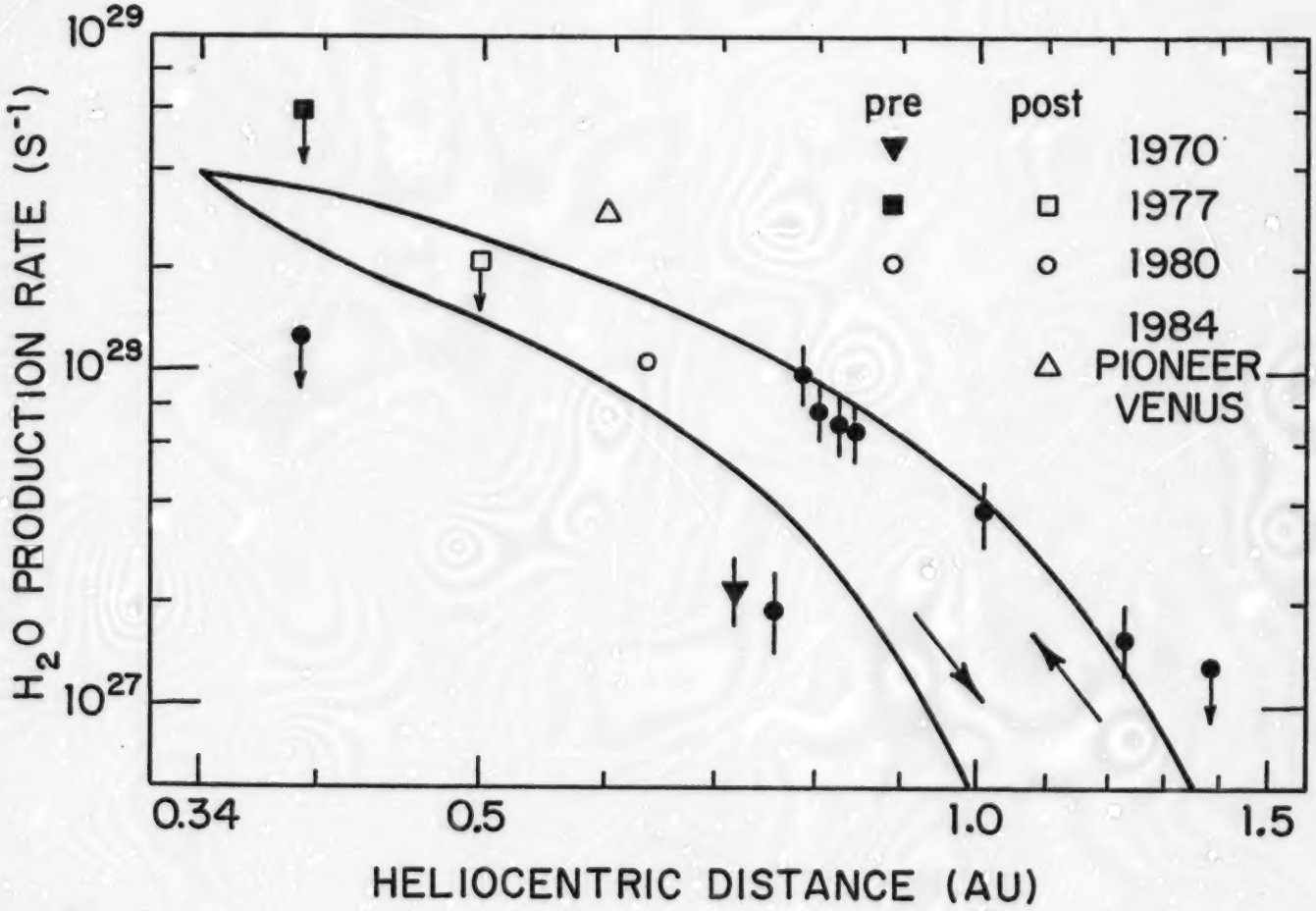
10^{29}
10^{28}
10^{27}
H_2O PRODUCTION RATE (S^{-1})
pre
post
1970
1977
1980
1984
PIONEER VENUS
0.34
0.5
1.0
1.5
HELIOCENTRIC DISTANCE (AU)

Figure 4